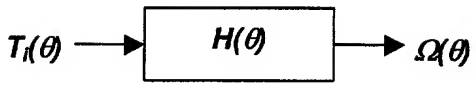


Fig. 1

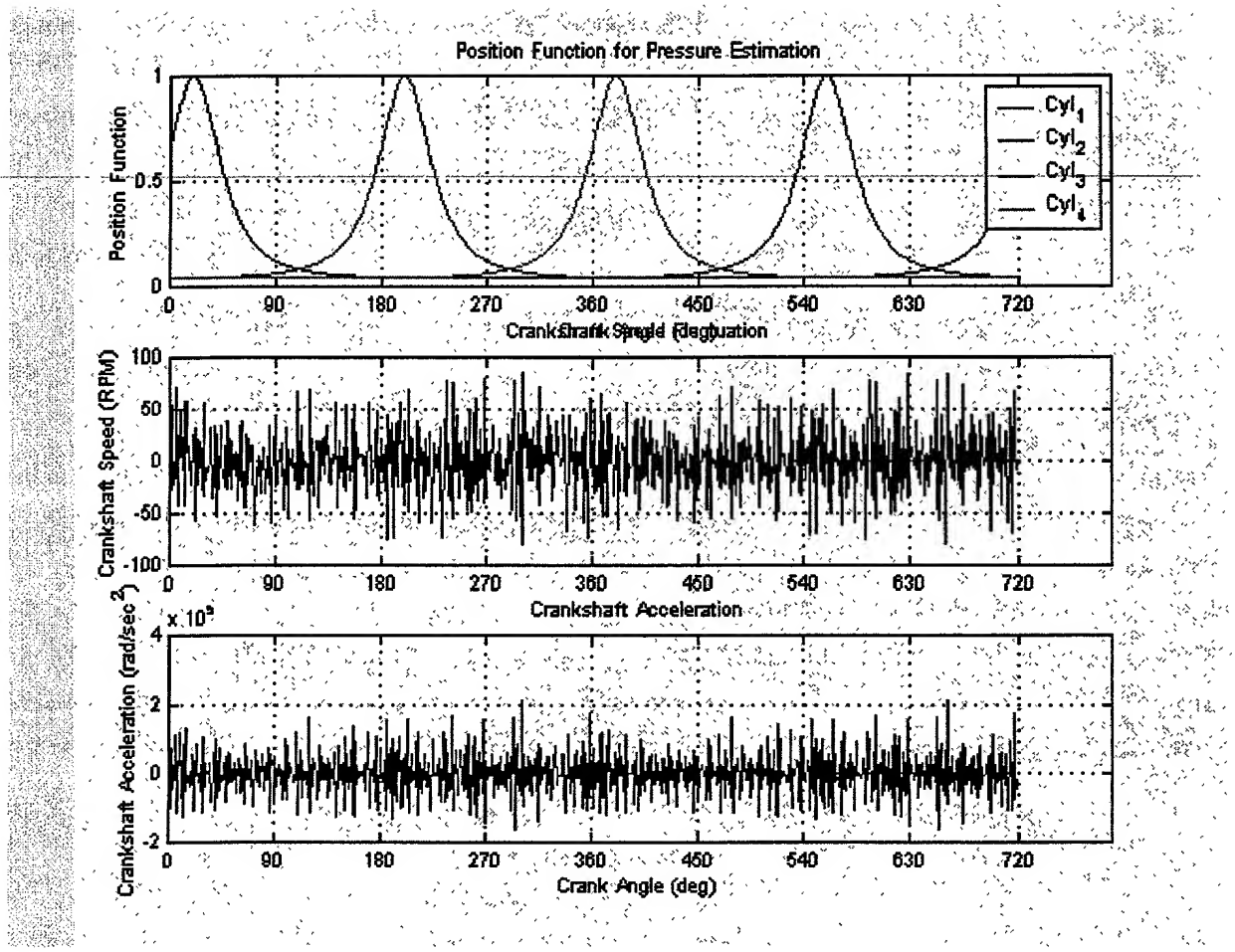

Position Function for Pressure Estimation
Position Function
Cyl1
Cyl2
Cyl3
Cyl4
Crankshaft Angle (degree)
Crankshaft Speed (RPM)
Crankshaft Acceleration
x 10^5
Crankshaft Acceleration (rad/sec^2)
Crank Angle (deg)

Fig. 2

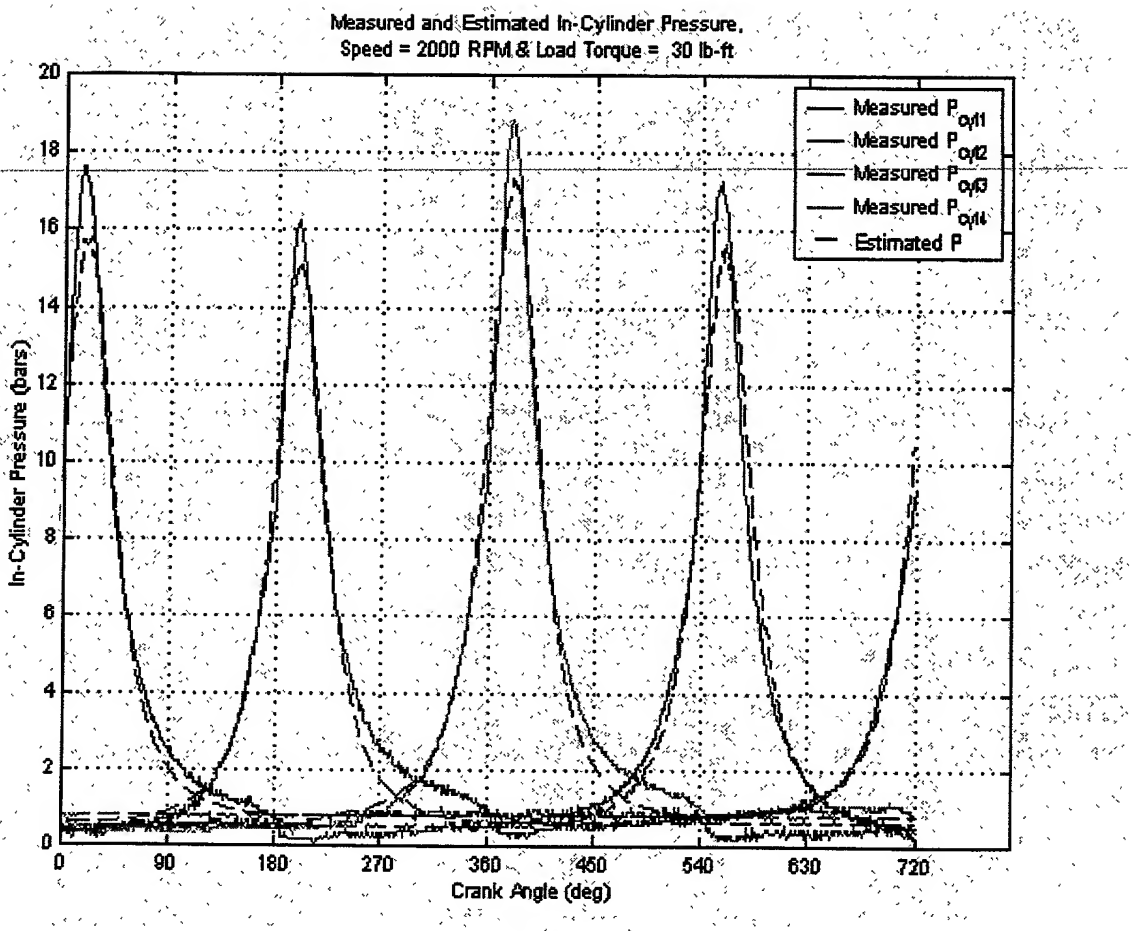

Measured and Estimated In-Cylinder Pressure,
Speed = 2000 RPM & Load Torque = 30 lb-ft
In-Cylinder Pressure (bars)
Crank Angle (deg)
Measured P cyl1
Measured P cyl2
Measured P cyl3
Measured P cyl4
Estimated P
0
2
4
6
8
10
12
14
16
18
20
0
90
180
270
360
450
540
630
720

Fig. 3

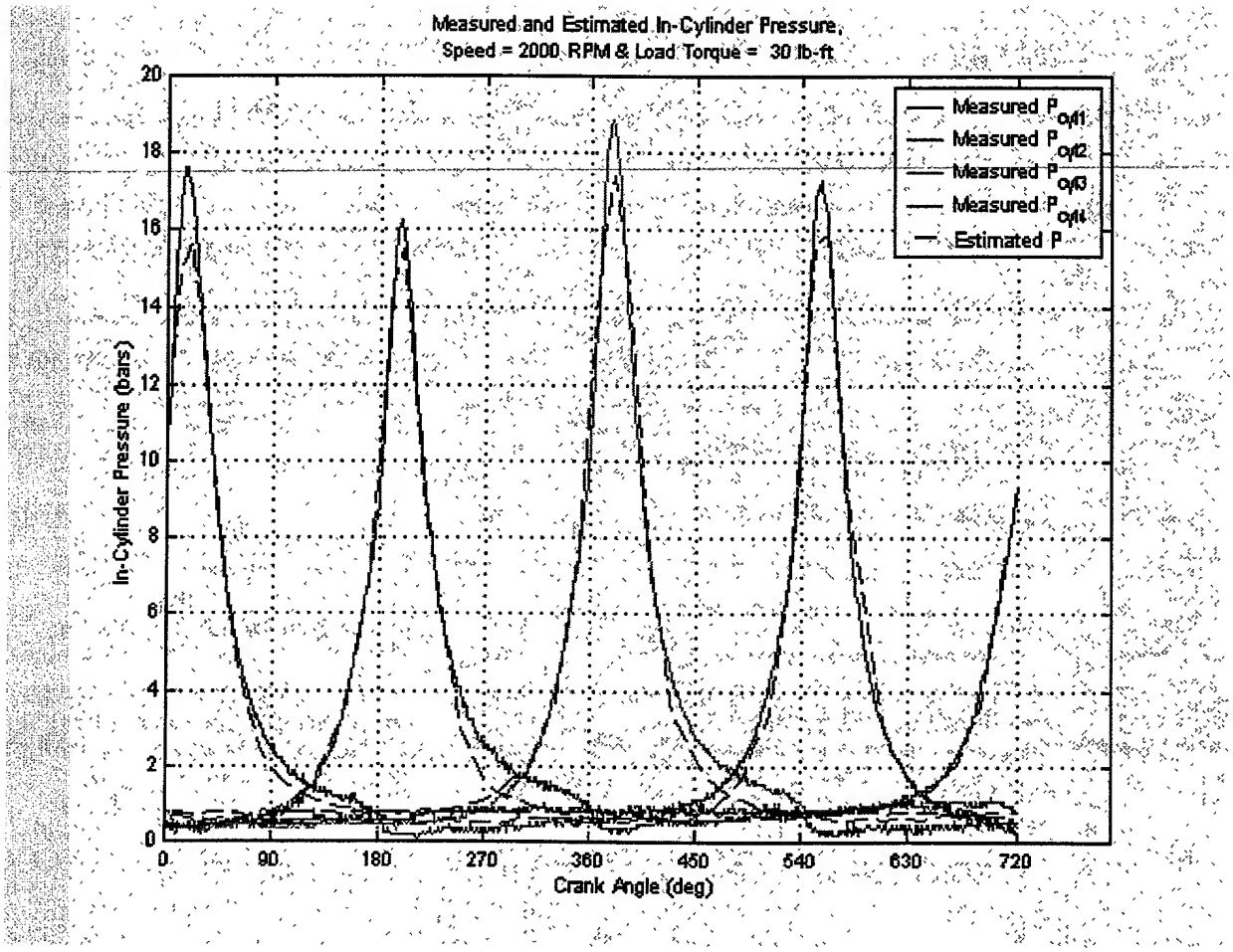

Measured and Estimated In-Cylinder Pressure,
Speed = 2000 RPM & Load Torque = 30 lb-ft
In-Cylinder Pressure (bars)
Crank Angle (deg)
Measured P cyl1
Measured P cyl2
Measured P cyl3
Measured P cyl4
Estimated P
0
2
4
6
8
10
12
14
16
18
20
90
180
270
360
450
540
630
720

Fig. 4

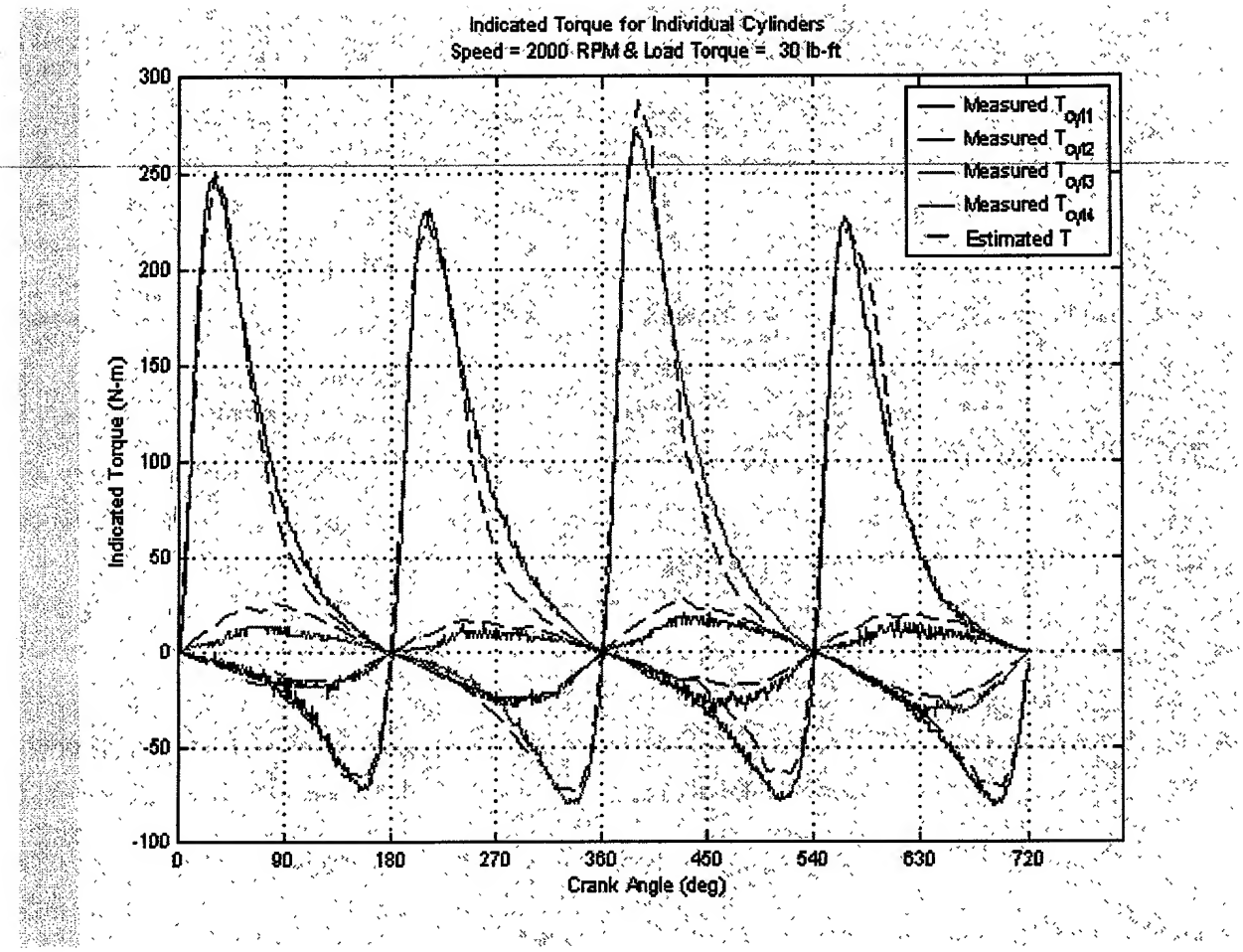

Indicated Torque for Individual Cylinders
Speed = 2000 RPM & Load Torque = 30 lb-ft
Measured T_ofi1
Measured T_ofi2
Measured T_ofi3
Measured T_ofi4
Estimated T
Indicated Torque (N-m)
Crank Angle (deg)
300
250
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720

Fig. 5

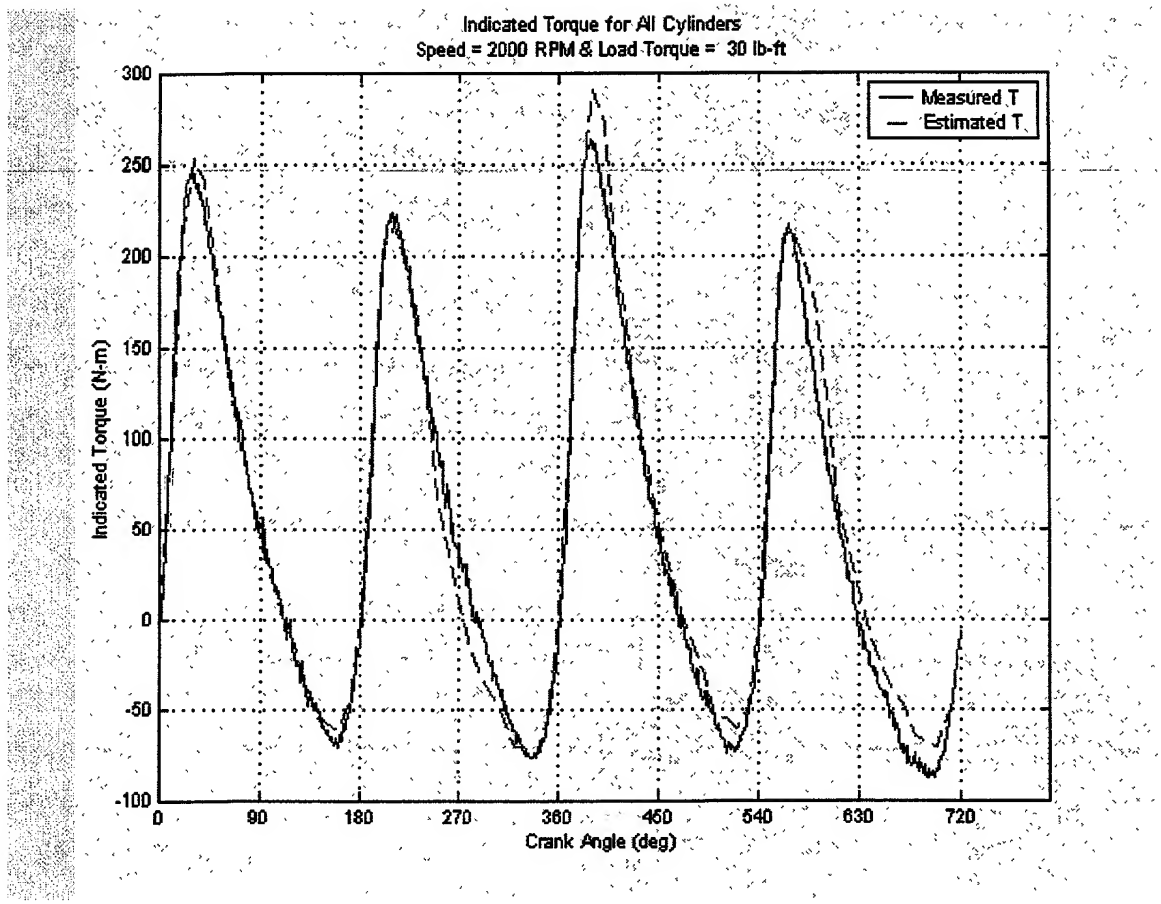

Indicated Torque for All Cylinders
Speed = 2000 RPM & Load Torque = 30 lb-ft
Measured T
Estimated T
Indicated Torque (N-m)
Crank Angle (deg)
300
250
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720

Fig. 6

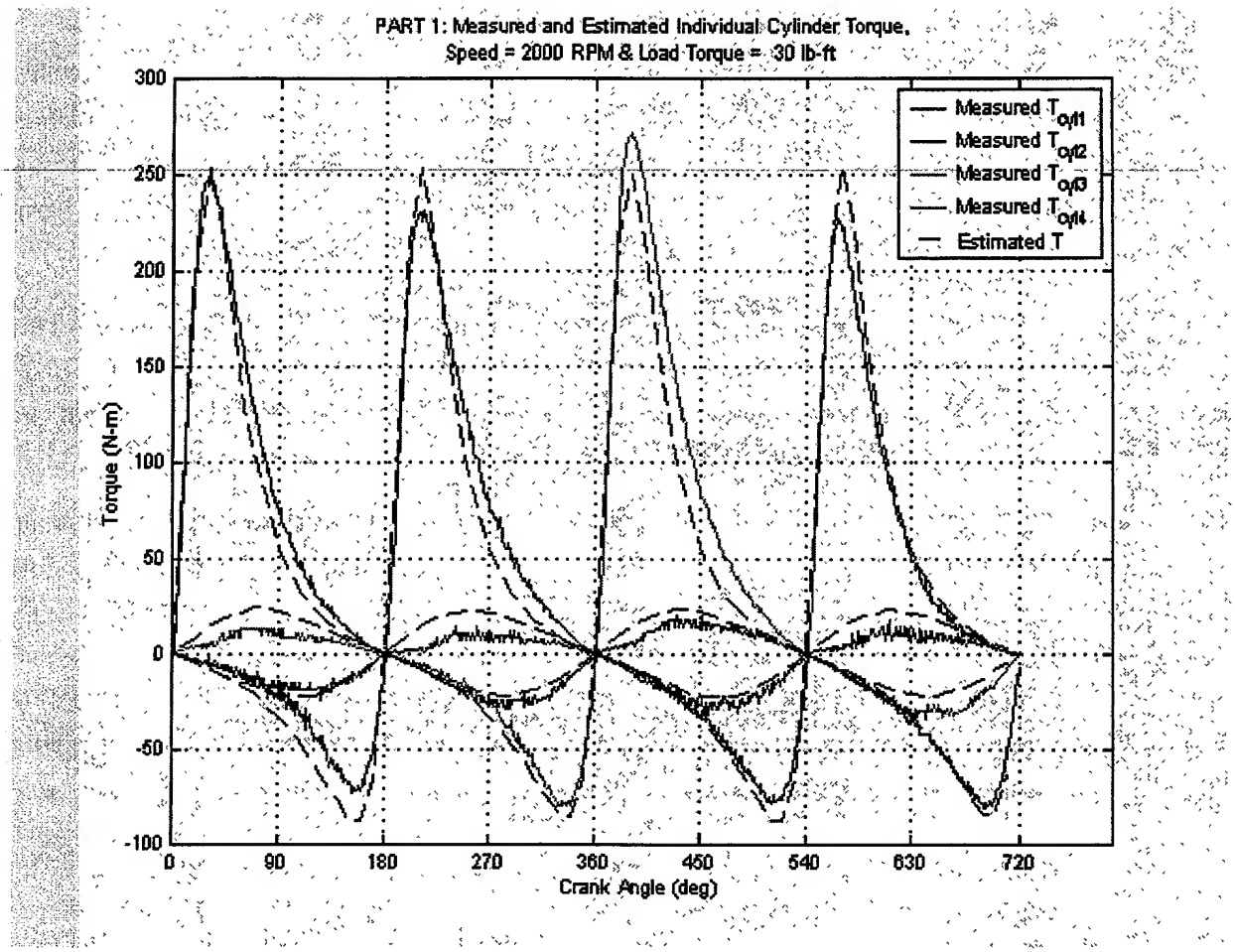

PART 1: Measured and Estimated Individual Cylinder Torque,
Speed = 2000 RPM & Load Torque = 30 lb-ft
Measured T_{cyl1}
Measured T_{cyl2}
Measured T_{cyl3}
Measured T_{cyl4}
Estimated T
Torque (N-m)
300
250
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720
Crank Angle (deg)

Fig. 7

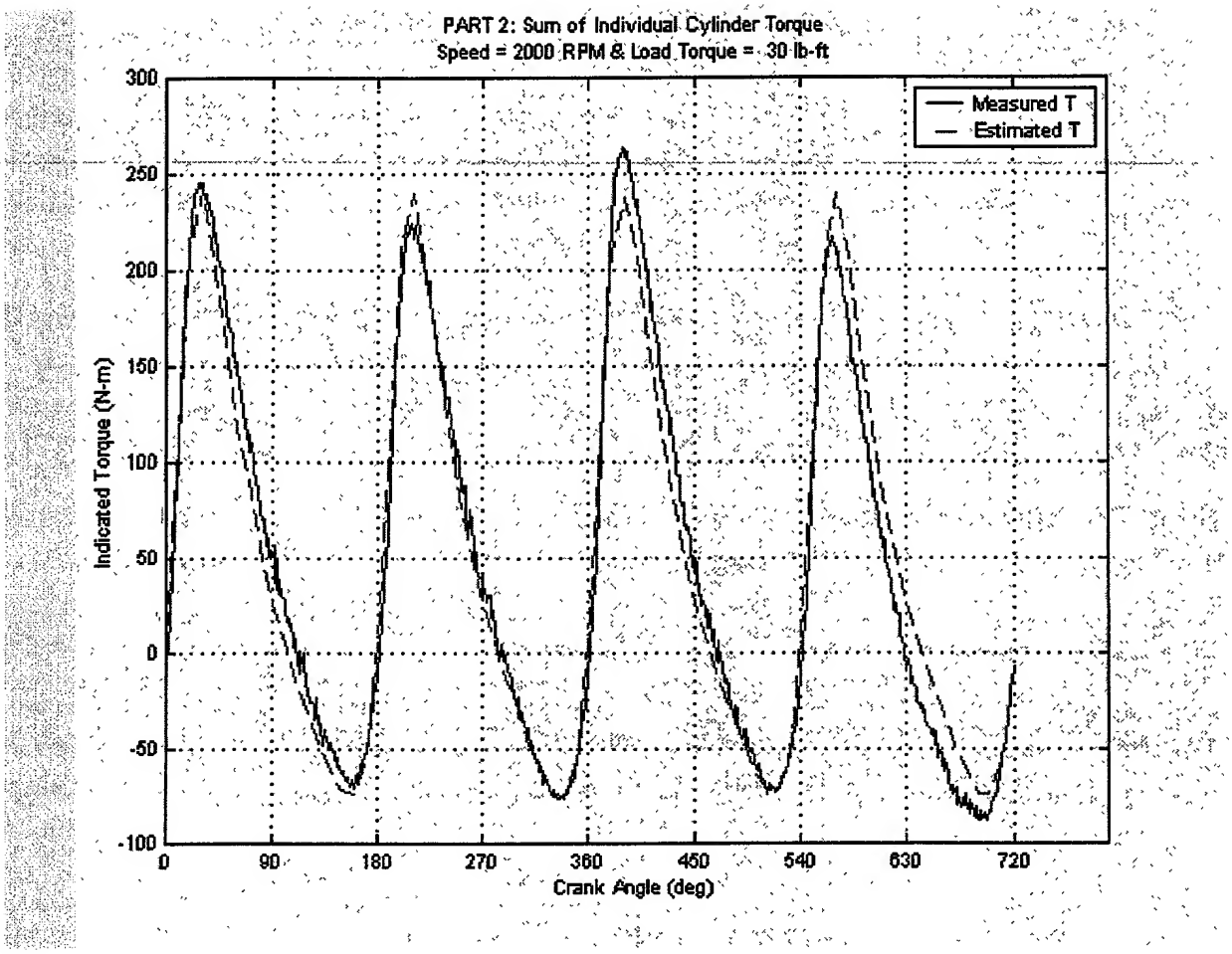

PART 2: Sum of Individual Cylinder Torque
Speed = 2000 RPM & Load Torque = 30 lb-ft
Measured T
Estimated T
Indicated Torque (N-m)
Crank Angle (deg)
300
250
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720

Fig. 8

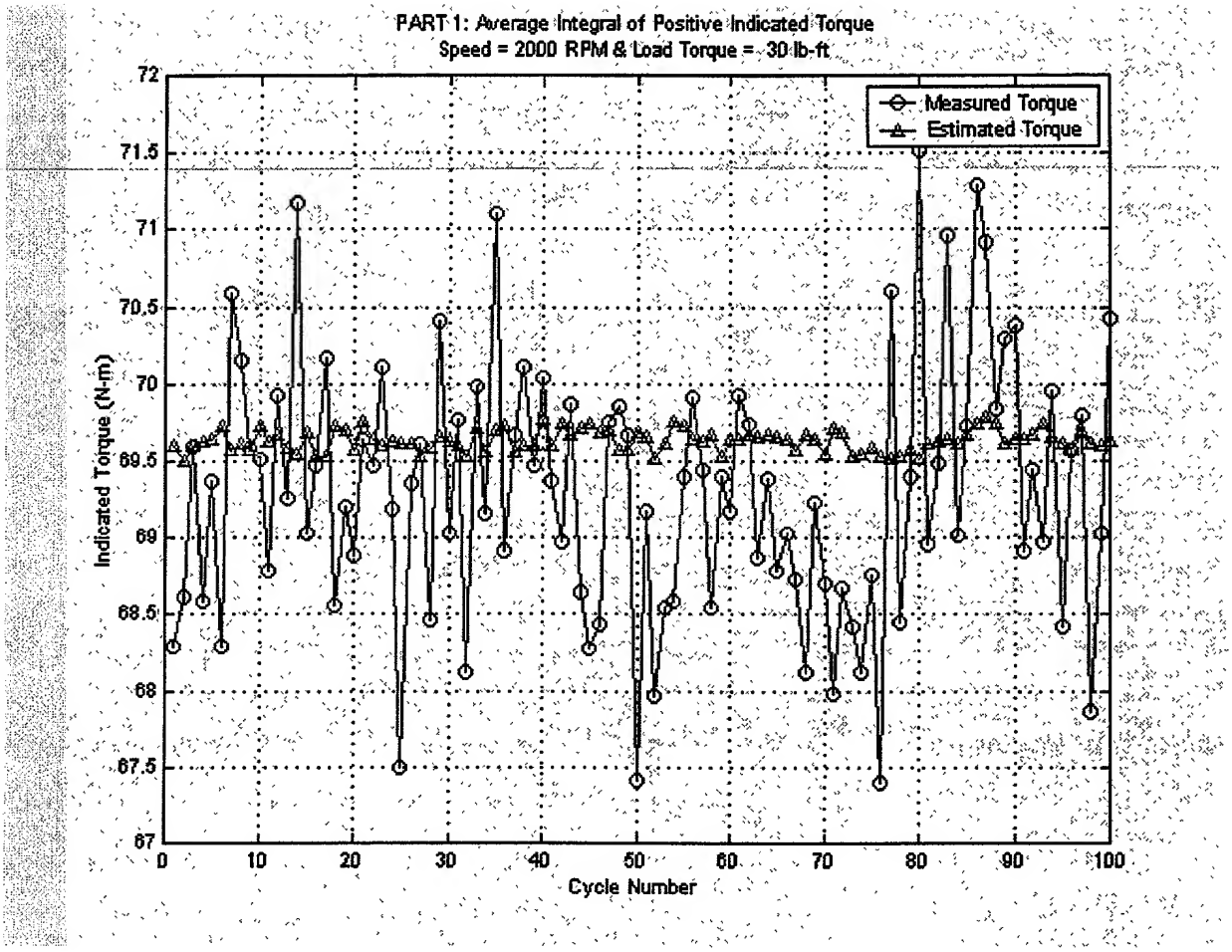

PART 1: Average Integral of Positive Indicated Torque
Speed = 2000 RPM & Load Torque = 30 lb-ft
Measured Torque
Estimated Torque
Indicated Torque (N-m)
Cycle Number
72
71.5
71
70.5
70
69.5
69
68.5
68
67.5
67
0
10
20
30
40
50
60
70
80
90
100

Fig. 9

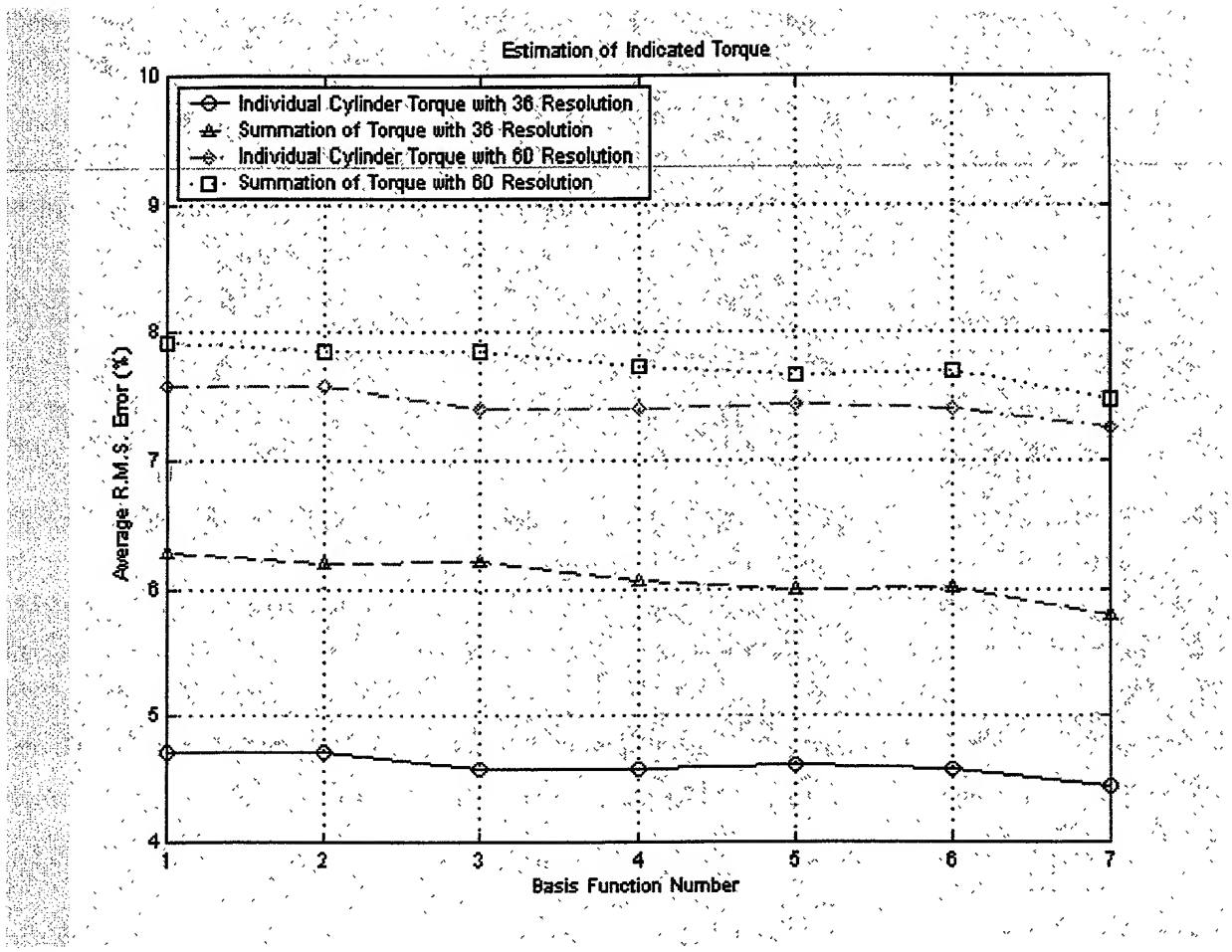

Estimation of Indicated Torque
Individual Cylinder Torque with 36 Resolution
Summation of Torque with 36 Resolution
Individual Cylinder Torque with 60 Resolution
Summation of Torque with 60 Resolution
Average R.M.S. Error (%)
Basis Function Number
10
9
8
7
6
5
4
1
2
3
4
5
6
7

Fig. 10

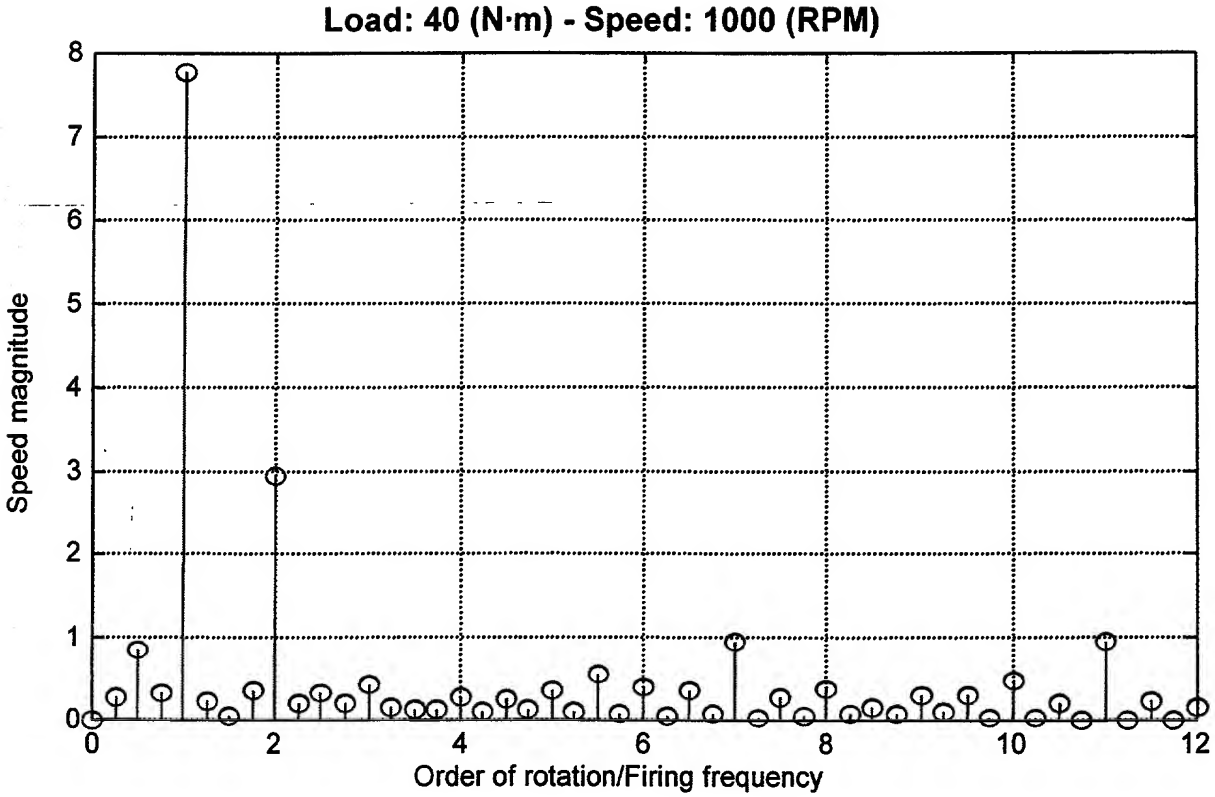

Load: 40 (N·m) - Speed: 1000 (RPM)
Speed magnitude
Order of rotation/Firing frequency
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12

Fig. 11

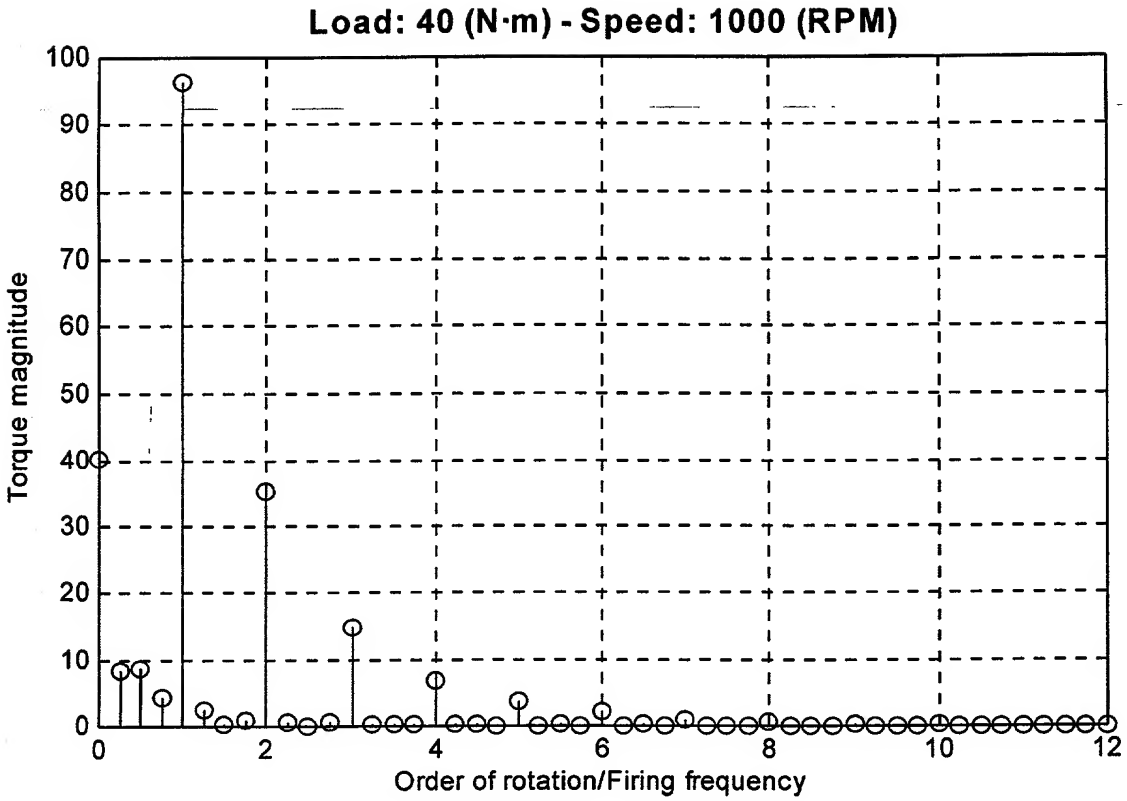
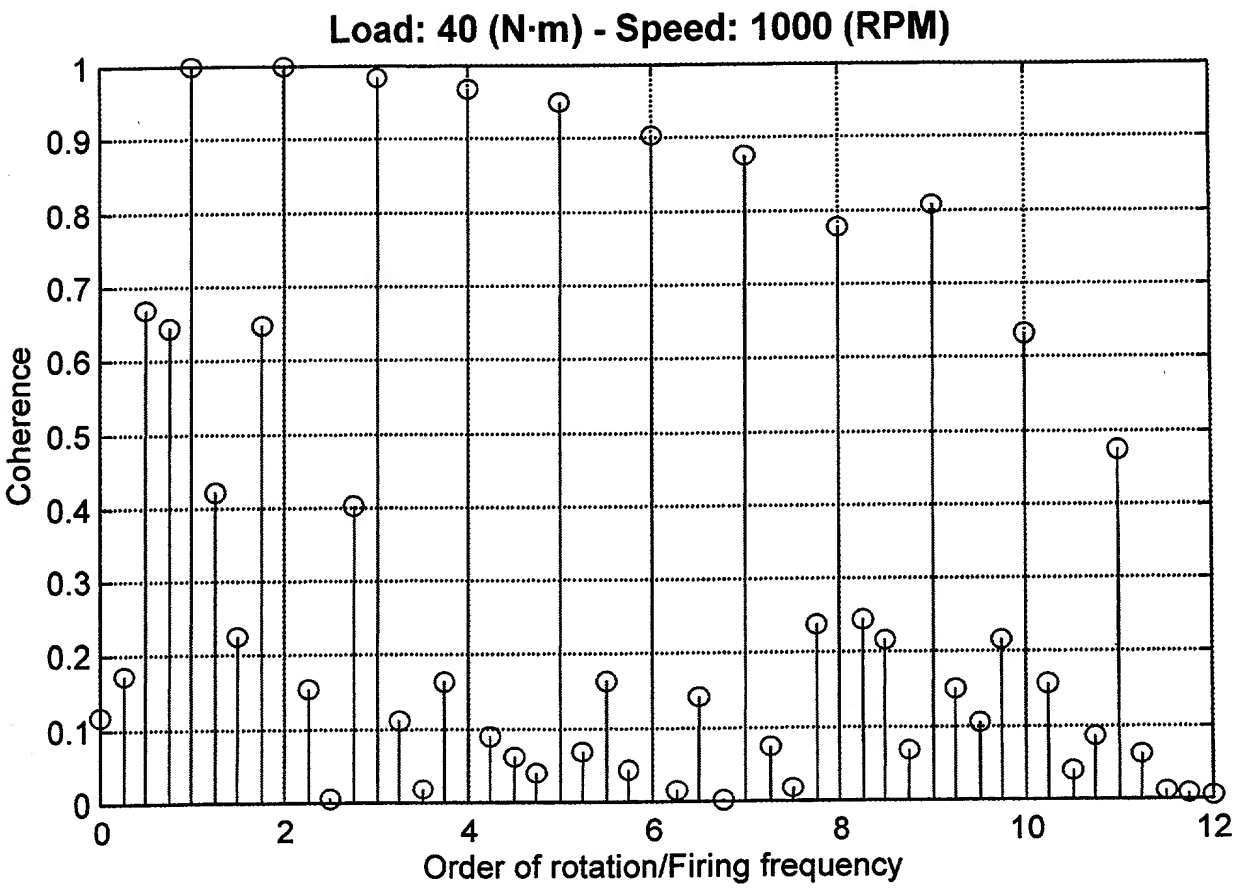

Load: 40 (N·m) - Speed: 1000 (RPM)
Torque magnitude
Order of rotation/Firing frequency
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12

Fig. 12

Fig. 13


Load: 40 (N·m) - Speed: 1000 (RPM)
Coherence
Order of rotation/Firing frequency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12

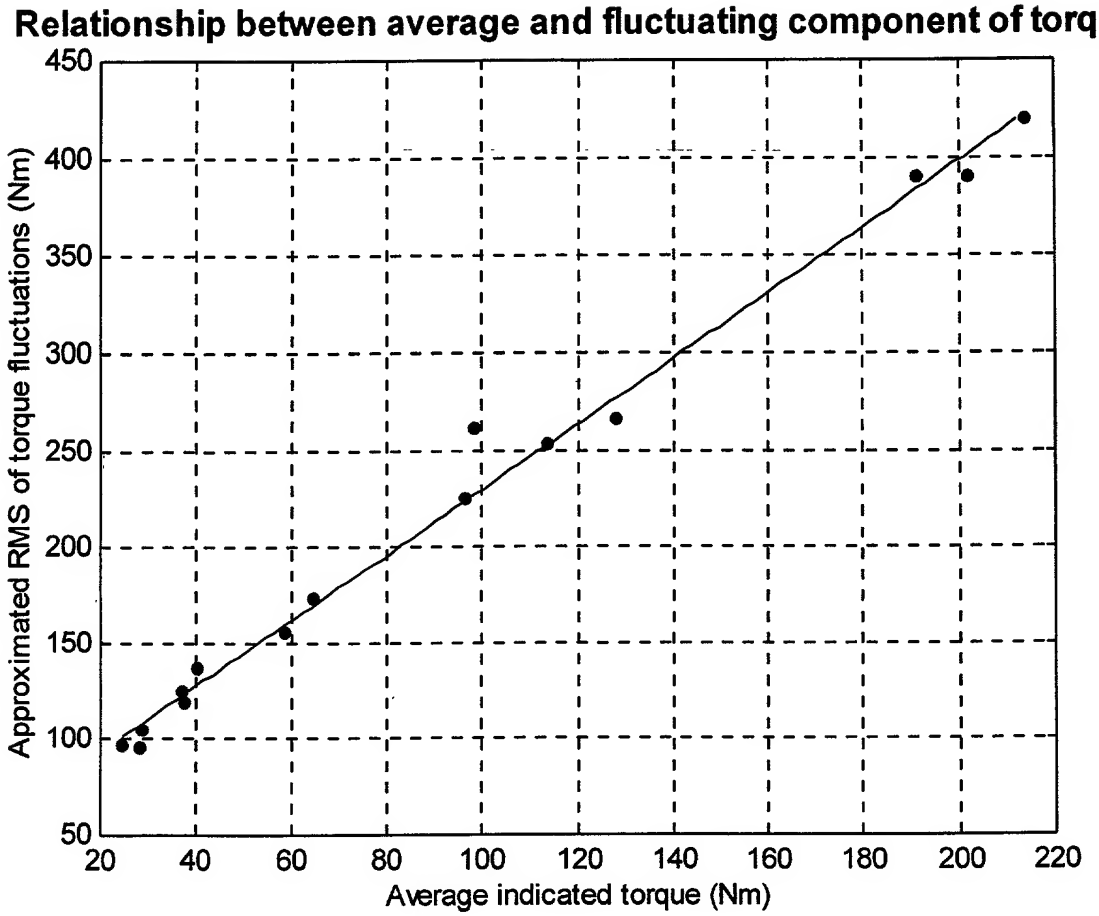

Relationship between average and fluctuating component of torque
Approximated RMS of torque fluctuations (Nm)
Average indicated torque (Nm)
450
400
350
300
250
200
150
100
50
20
40
60
80
100
120
140
160
180
200
220

Fig. 14

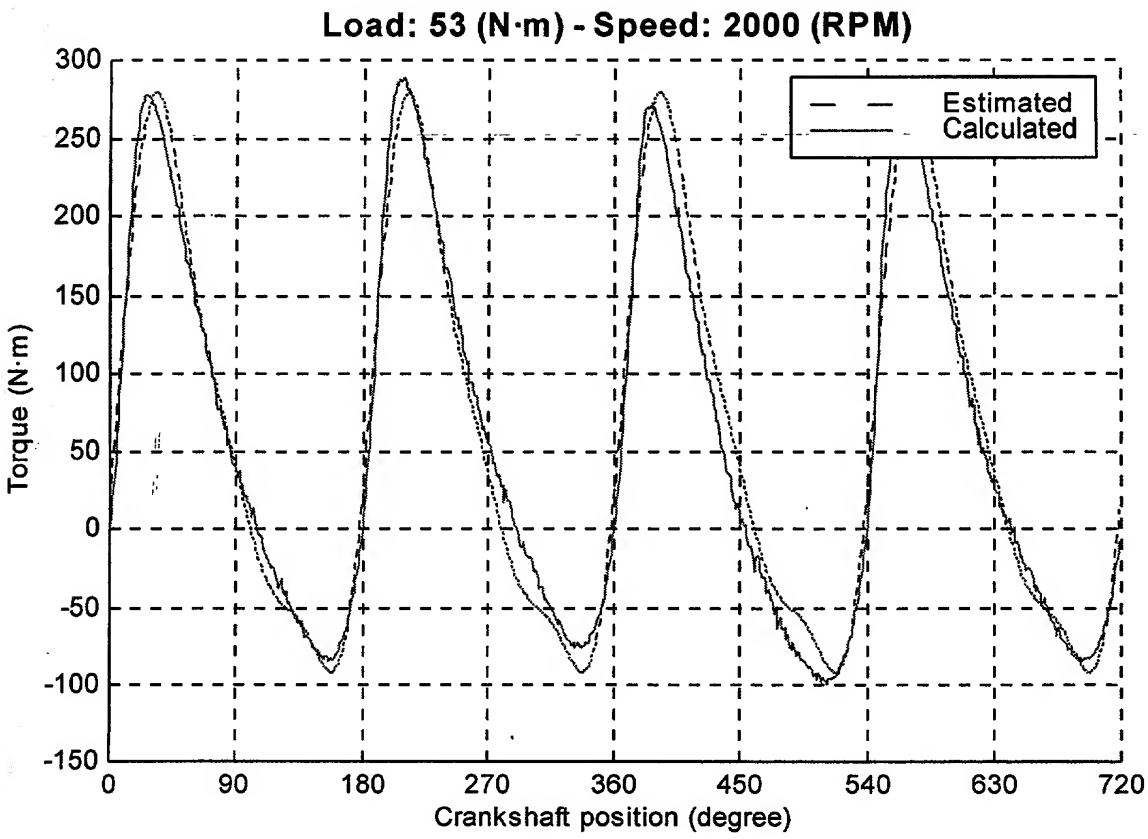

Load: 53 (N·m) - Speed: 2000 (RPM)
Estimated
Calculated
Torque (N·m)
Crankshaft position (degree)
300
250
200
150
100
50
0
-50
-100
-150
0
90
180
270
360
450
540
630
720

Fig. 15

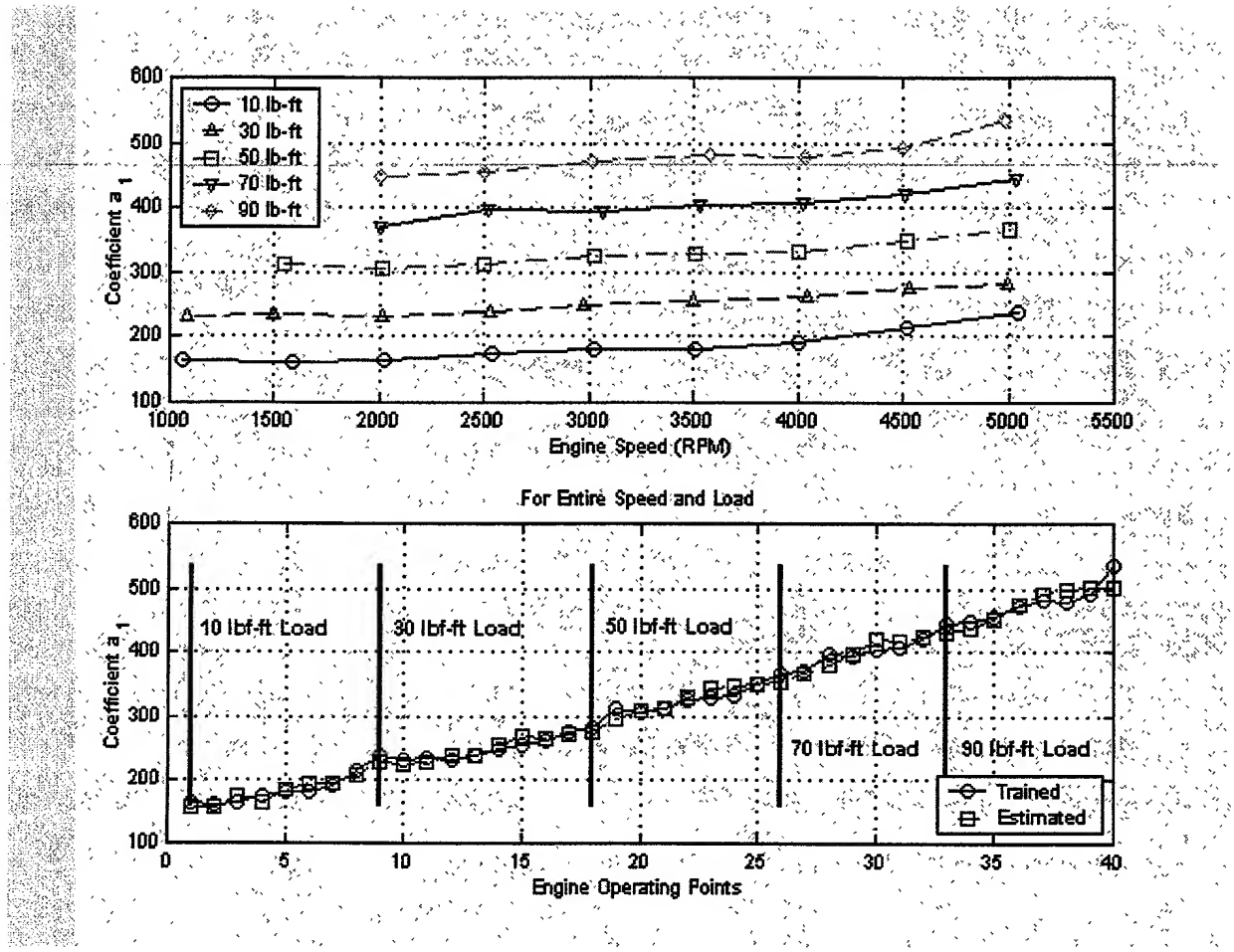

10 lb-ft
30 lb-ft
50 lb-ft
70 lb-ft
90 lb-ft
Coefficient a 1
Engine Speed (RPM)
For Entire Speed and Load
10 lbf-ft Load
30 lbf-ft Load
50 lbf-ft Load
70 lbf-ft Load
90 lbf-ft Load
Trained
Estimated
Engine Operating Points

Fig. 16

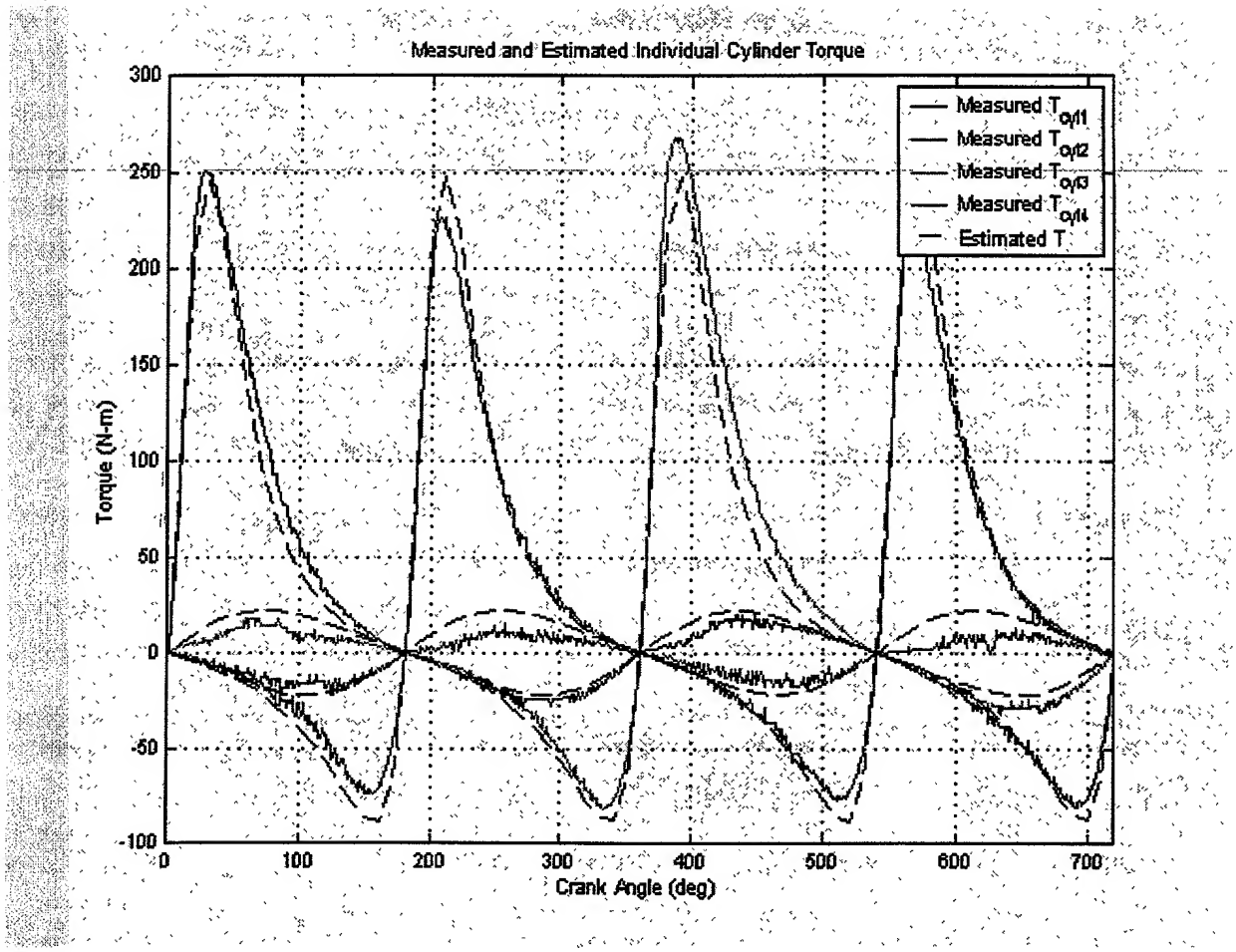

Measured and Estimated Individual Cylinder Torque
Measured $T_{c/l1}$
Measured $T_{c/l2}$
Measured $T_{c/l3}$
Measured $T_{c/l4}$
Estimated T
Torque (N-m)
Crank Angle (deg)
300
250
200
150
100
50
0
-50
-100
0
100
200
300
400
500
600
700

Fig. 17

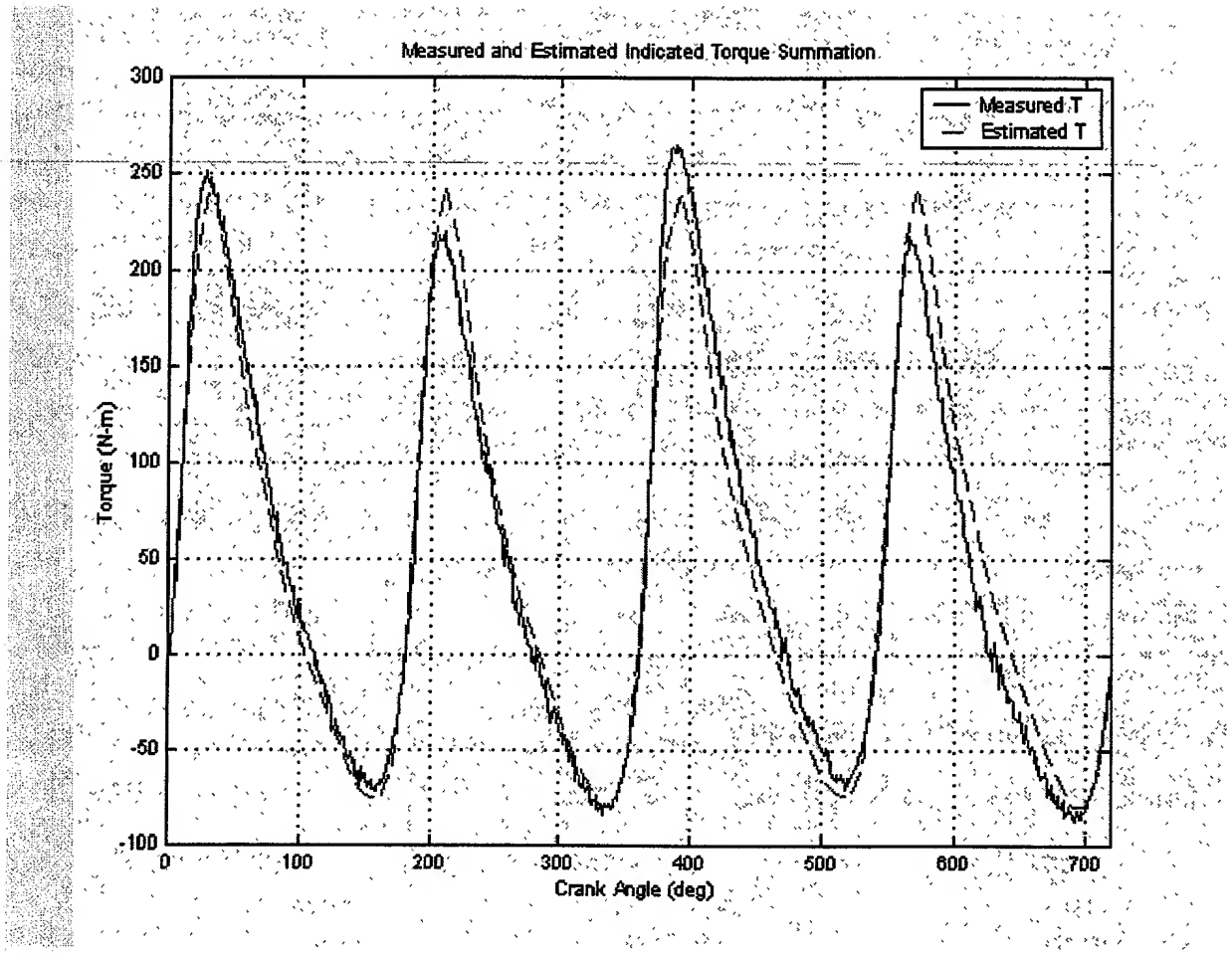

Measured and Estimated Indicated Torque Summation
Measured T
Estimated T
Torque (N-m)
Crank Angle (deg)
300
250
200
150
100
50
0
-50
-100
0
100
200
300
400
500
600
700

Fig. 18

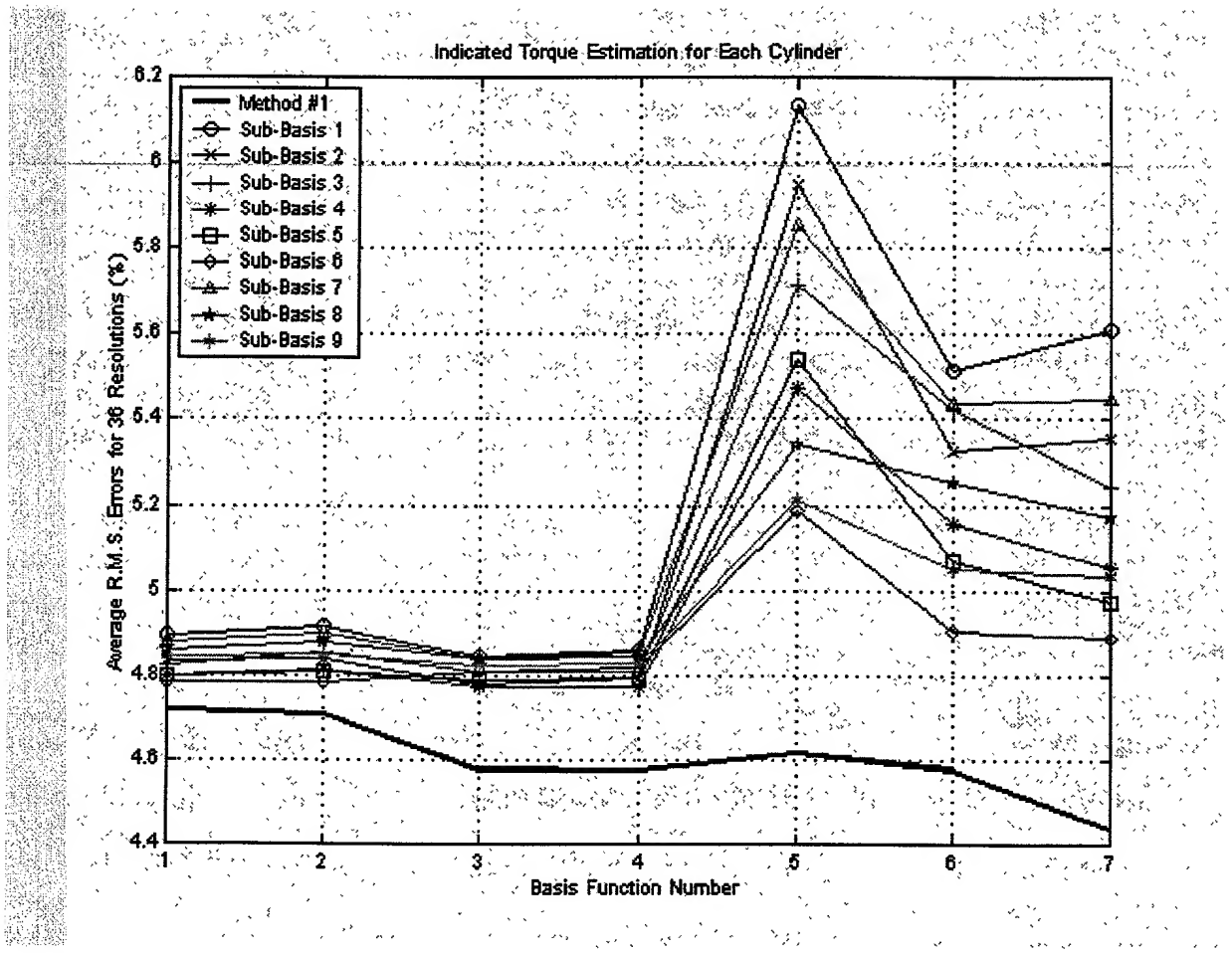

Indicated Torque Estimation for Each Cylinder
Method #1
Sub-Basis 1
Sub-Basis 2
Sub-Basis 3
Sub-Basis 4
Sub-Basis 5
Sub-Basis 6
Sub-Basis 7
Sub-Basis 8
Sub-Basis 9
Average R.M.S. Errors for 36 Resolutions (%)
Basis Function Number
6.2
6
5.8
5.6
5.4
5.2
5
4.8
4.6
4.4
1
2
3
4
5
6
7

Fig. 19

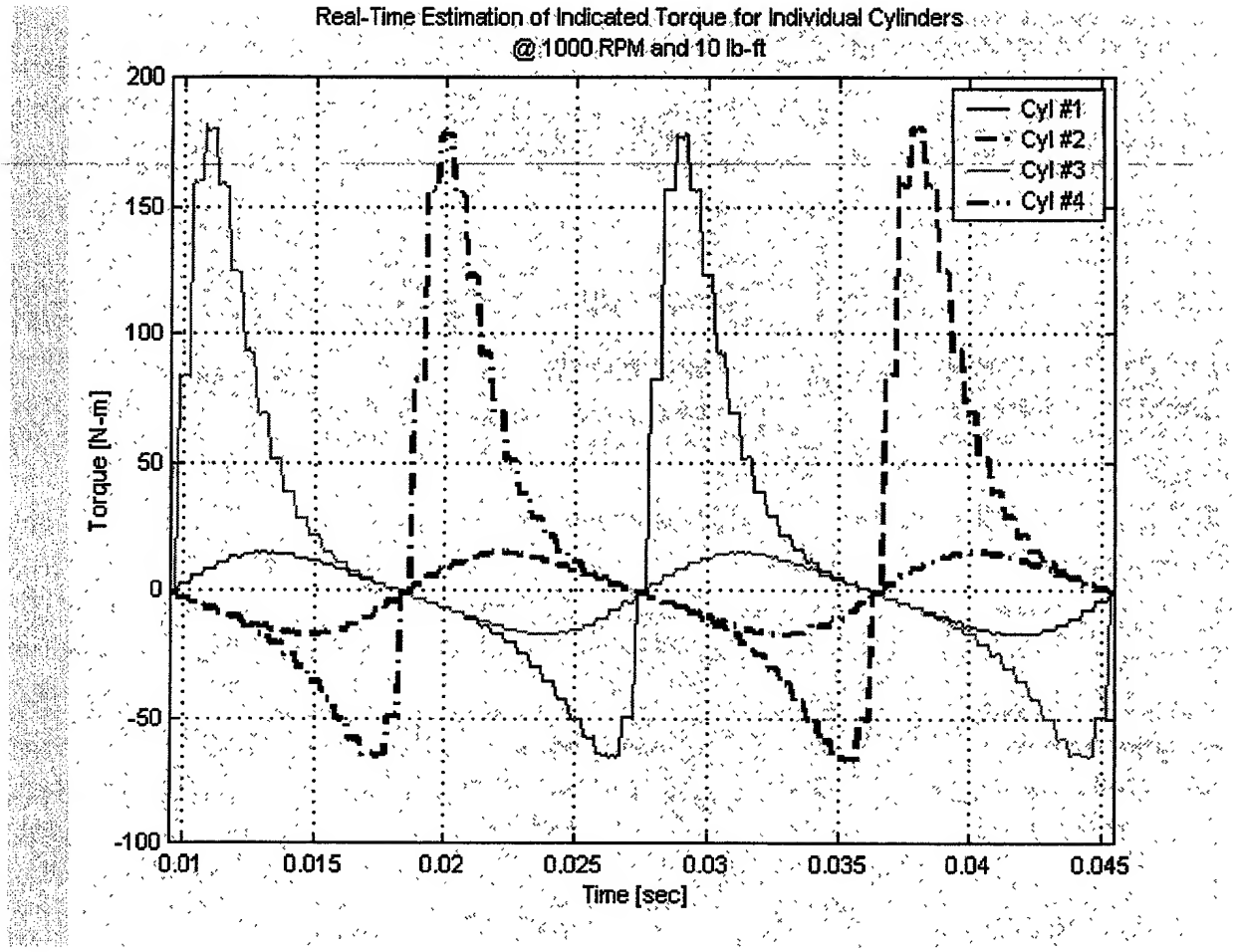

Real-Time Estimation of Indicated Torque for Individual Cylinders
@1000 RPM and 10 lb-ft
Cyl #1
Cyl #2
Cyl #3
Cyl #4
Torque [N-m]
Time [sec]
200
150
100
50
0
-50
-100
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045

Fig. 20

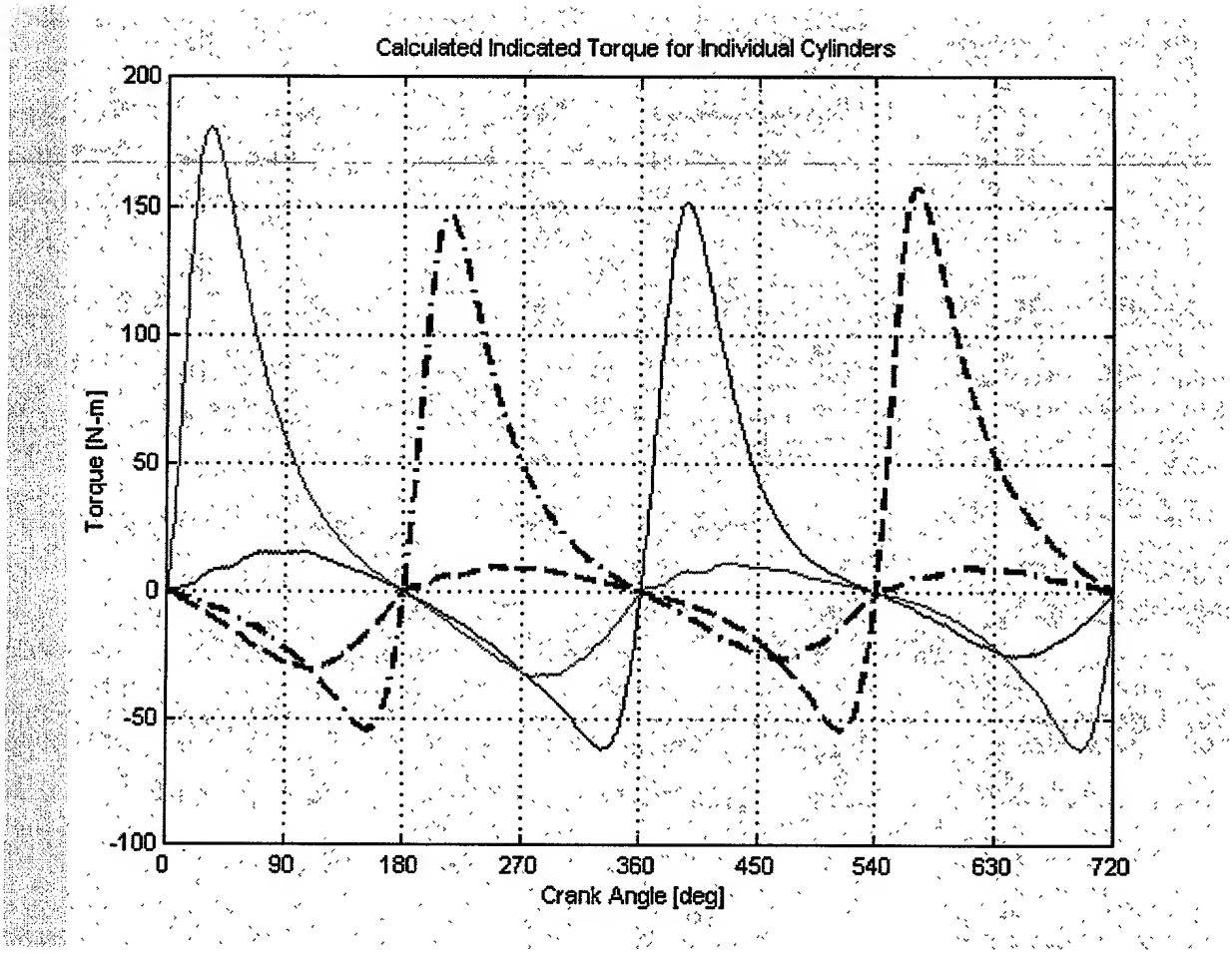

Calculated Indicated Torque for Individual Cylinders
Torque [N-m]
Crank Angle [deg]
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720

Fig. 21

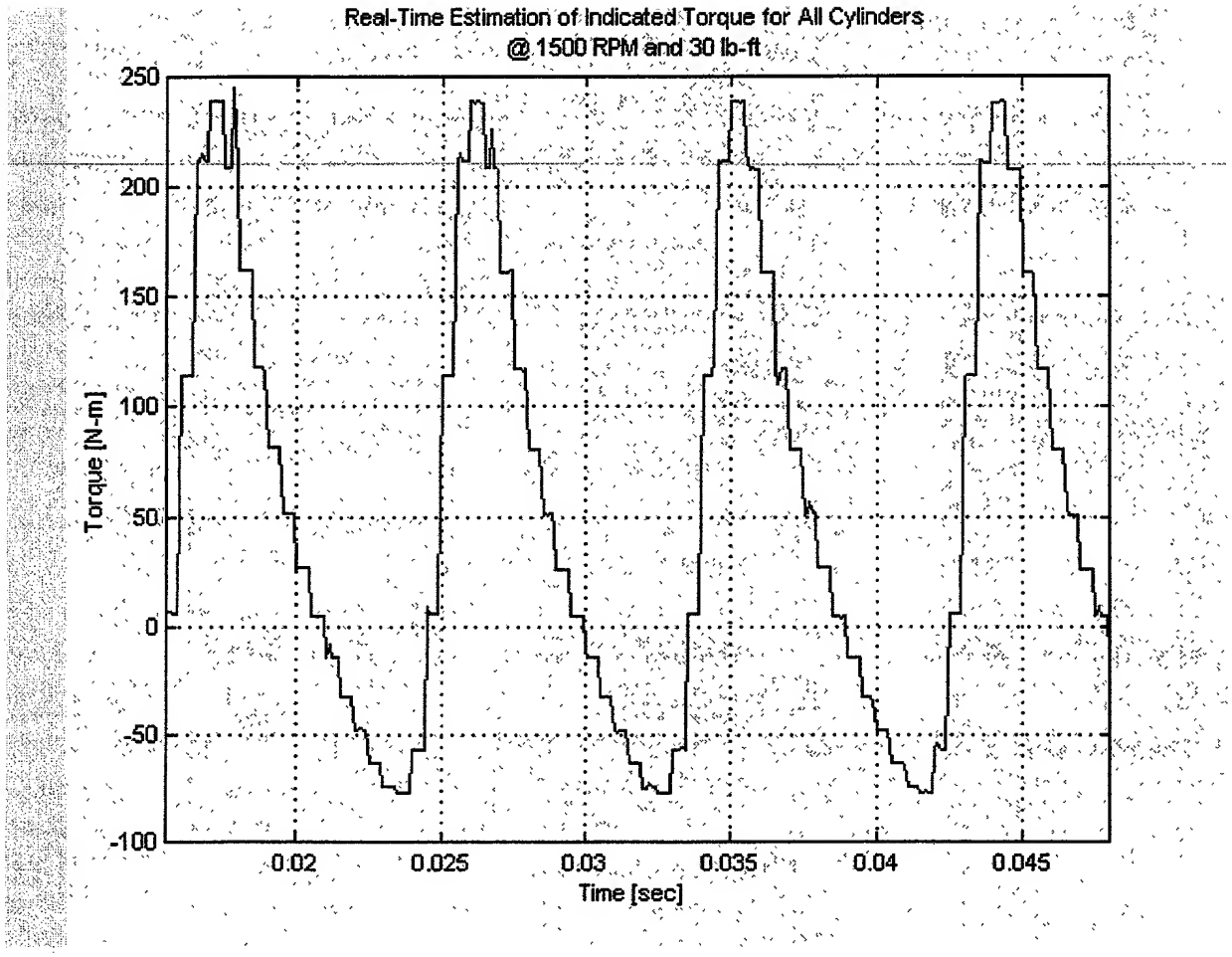

Real-Time Estimation of Indicated Torque for All Cylinders
@ 1500 RPM and 30 lb-ft
Torque [N-m]
Time [sec]
250
200
150
100
50
0
-50
-100
0.02
0.025
0.03
0.035
0.04
0.045

Fig. 22

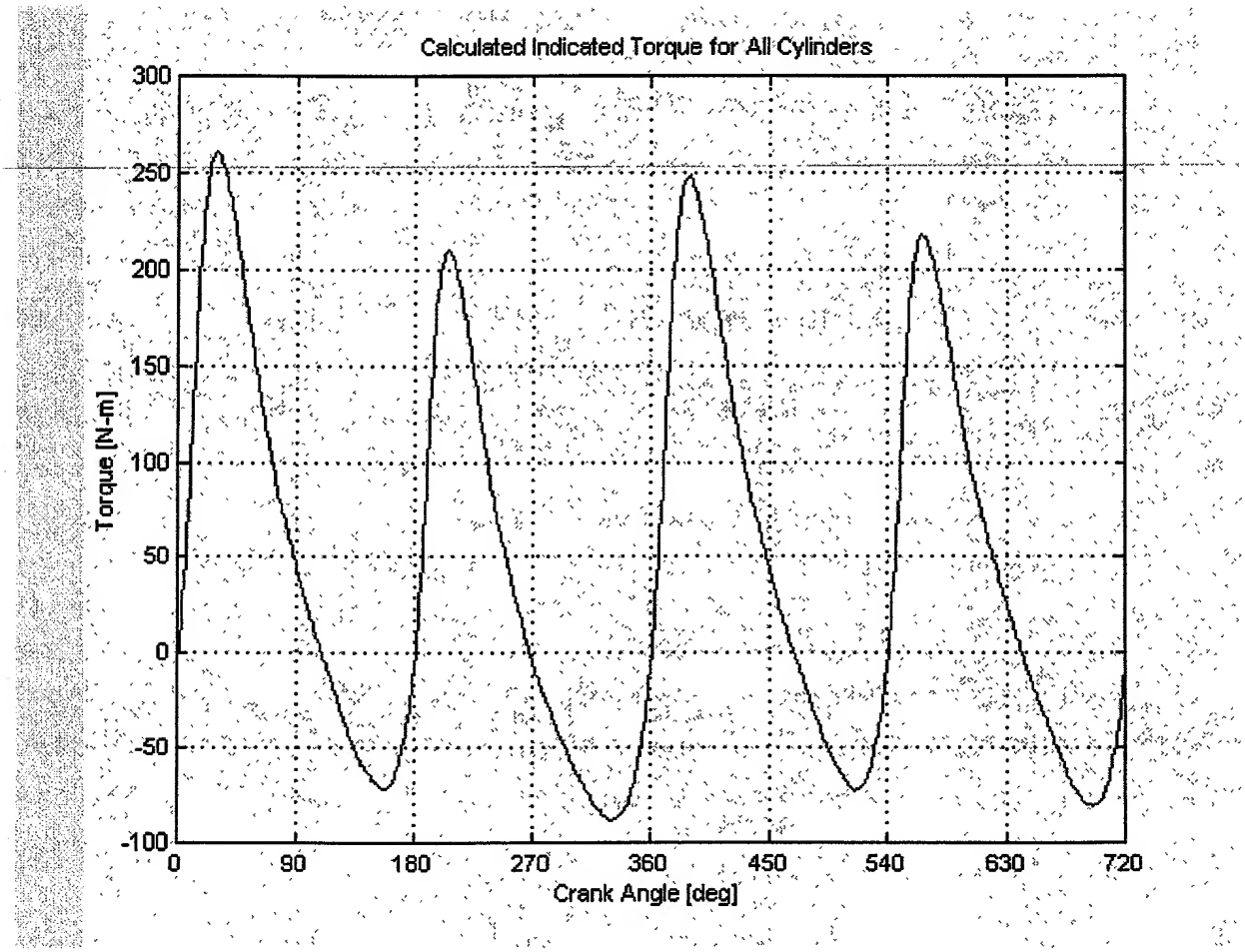

Calculated Indicated Torque for All Cylinders
Torque [N-m]
300
250
200
150
100
50
0
-50
-100
0
90
180
270
360
450
540
630
720
Crank Angle [deg]

Fig. 23